FY97 End of Fiscal Year Letter
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ONR Contract Information

Contract Title:	**ULTRALIGHT METAL STRUCTURES**
Performing Organization:	Harvard University
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Contract Number:	N00014-96-1-1028
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A. RESEARCH AND DEVELOPMENT GOALS

The major challenge for implementation of cellular metals involves their multifunctional nature. That is, their performance attributes relative to competing materials are rarely based on a single property category. Moreover, few applications rely solely on specific mechanical or thermal properties. Combinations of these with other attributes, such as energy absorption, acoustic damping, etc. provide a performance benefit. Furthermore, implementation opportunities may not depend on performance, but rather on cost relative to other systems. The program is structured with this perspective. It combines property measurement and simulation with thermostructural concepts for components, code development, innovative processing concepts, data bases containing thermomechanical performance indices and software.

To address multifunctionality, the CMS software will be expanded to include a cellular metals data base. A Shape subroutine has also been developed that interrelates materials selection with structurally efficient shapes, such as I-beams. That is, it mutually selects the minimum weight configuration and the preferred material. Extension to foam core configurations will be an essential step toward establishing ULS performance benefits.

Minimum weight design represents one aspect of cellular metal performance. An analysis of such designs for uniaxially compressed tubes and panels has identified configurations and loading domains wherein foam core construction provides weight savings. One example comprises a skin/stringer panel wherein both the panel and the stringers have optimum thickness face sheets and foam cores. Analyses of other configurations and of more complex loadings will establish "generic" weight reduction strategies.

For cellular metals to provide structural or thermal performance benefits, the material requires "non-defective" cell architectures. One of the goals is to identify the defects that degrade the performance, such that manufacturing strategies capable of creating materials with the minimum number density of such defects, at low cost, can be put in place. A first aspect of this strategy is to define the "best-possible" properties for a material with regular, isotropic cells and, thereby, establish the property "knock-down" for commercially available materials. The main findings are as follows.

(i) The best mechanical performance is provided by the closed cell ALPORAS material. However, its modulus is 1/2 to 1/3 that for the regular solid and, moreover, the knock-down factor on yield strength is larger: 1/3 to 1/4. The ERG material has properties comparable to those expected for the regular open cell solid, but they are inferior to those for the ALPORAS material, absent membrane stiffening and strengthening.

(ii) The ability of open cell materials to dissipate or recuperate heat relates to the high thermal conduction along the cell walls and the effect of the cells on the fluid flows. A model of this process in combination with experimental measurements of the gas and metal temperatures have indicated directions for creating materials with heat transfer capabilities needed to satisfy compact heat exchanger and heat dissipation applications.

B. SIGNIFICANT RESULTS

I. Selection and Design Software

Addition of a cellular metals data base to the CMS software has provided a basis for exploring combinations of attributes that provide similar or better performance at costs lower than competing materials and concepts. The data are being periodically updated with results generated in the MURI program and elsewhere.

A new feature of the software comprises a Shape subroutine that simultaneously addresses materials and configurations for minimum weight structures. It compares and contrasts the weight efficiency of commonly used shapes, subject to user defined loadings and size constraints. In this manner, it selects the preferred material and shape. Extension of this capability to include foam core construction will address one of the main implementation challenges.

II. Minimum Weight Design

Analysis of minimum weight configurations for tubes and panels subject to uniaxial compressive loads has identified loading and configurational domains wherein foam core construction has weight advantages over conventional construction. These arise when the loading indices reside in the elastic range and when foam core construction is used either for the walls of tubes or for both the stiffeners and face sheets of panels. Extension of the analysis to shells and to other loadings is expected to identify additional situations wherein foam cores offer weight savings.

III. Morphological Defects

By means of X-ray CAT scan and optical imaging methods as well as mechanical measurements and simulations, the morphologies of closed cell solids that cause the "knock down" in mechanical properties have been explored. At the simplest level, the cell aspect ratio has been found to be a dominant feature, whereas cell size has only secondary importance. That is, cells with an elliptical cross section oriented with their long axis normal to the loading direction are found to be susceptible to yielding, while equiaxed cells resist yielding, whatever their size. Moreover, an array of contiguous elliptical cells on a plane normal to the loading axis appears to act as the "defect" that initiates yielding by formation of a collapse band. All of the displacements in this band are normal to its plane, indicative of bending or buckling modes of yielding. The analogous three-dimensional picture is more complex and not yet fully-resolved.

IV. Thermal Performance

A model has been developed that establishes the effects of material properties and fluid flows on the heat transfer and pressure drops associated with open cell metals. Experimental measurements have confirmed some of the theoretically predicted heat transfer trends and provided a calibration of the coefficient that scales the pressure drop accompanying fluid flow through the material. The presently available materials are found to be deficient in their heat transfer capabilities. However, using the theoretical model and the experimentally determined calibration coefficient, it is possible to specify the characteristics of cellular metals that achieve the very high heat transfer rates needed for heat exchange applications and satisfy cooling requirements for high power electronics.

Major improvements could be realized by creating a cellular Al or Cu material with a small cell ligament thickness ($\sim 50\mu m$) and an intermediate relative density (~ 0.3).

V. Processing and Manufacturing

The manufacturing a foam in the liquid state has been investigated by theoretical models and laboratory experiments with aqueous foams. The model has been developed, based upon recent ideas published in the literature, expanded to characterize several relevant questions: free-drainage of an initially uniform foam and pulsed drainage of a foam with a localized region of additional liquid. Time-scales for evolution of the foam have been identified and related to the materials parameters (density, viscosity, and surface tension) as well as the typical bubble size. Also, a steady-state model of a continuous foam casting process has been developed. Laboratory experiments with aqueous foams suggest the possibility of improved control of bubble size in a gas injection process by using a porous material adjacent to the gas injector in order to produce smaller bubbles than are otherwise possible.

C. PLANS FOR 1998

The major activities for 1998 emphasize engineering requirements and manufacturing strategies. They comprise measurements, models, process innovation, software and code development.

(i) Properties and performance issues concern fatigue, creep, heat transfer, acoustic damping and energy absorption, as well as sub-element testing and analysis.

(ii) Processing interests embrace hollow sphere production and consolidation, blister control for low density core (LDC) manufacturing, the control of cell collapse in foam casting, and rapid prototyping of truss structures.

(iii) Software and code development emphases include enhancements to the CMS software with structural indices for cellular metal components, as well as constitutive laws suitable for numerical analysis and design.

I. Structural Performance

(i) Fatigue

Cellular metals are subject to fatigue in compression, tension and shear. Fatigue crack growth studies $[da/dN(\Delta K)]$ will be completed and correlated using a ligament bridging model, with a Coffin-Manson criterion for ligament failure.

Softening effects that occur in compression/compression loading will be measured and related to the cyclic flexural rupture of the cell walls. Initial results will be obtained for low cycle fatigue (LCF) using strain mapping and X-ray CAT scans to identify the softening mechanisms in the cell walls. Thermal imaging will be used to measure the associated rates of heat generation. Various R-ratios will be used to obtain a comprehensive understanding.

Some tests will be conducted at high frequencies in order to assess the high cycle fatigue (HCF) mechanism relevant to strain isolation applications.

The compressive softening and tensile crack growth phenomena will be used to analyze flexural fatigue results to be provided by UTRC.

(ii) Creep

A creep testing and modeling activity will be emphasized, initially for the ERG and ALPORAS materials, with the objective of relating the material deformation properties to those for the alloy comprising the cell walls, the relative density and the cell morphology, analogous to the relationships developed for stiffness and strength. Secondary and tertiary creep model will be developed that can be used to interpolate creep phenomenon over ranges of stress and temperature relevant to design and life prediction.

(iii) Sub-Element Testing and Analysis

Shear stress/strain curves will be measured with the cellular material bonded to steel end-plates. Strain mapping will be used to monitor the deformation heterogeneity. The tests will be performed on specimens with thicknesses ranging from 1 to 20 cell diameters, in order to explore the influence of the rotational constraint arising at the bonded interface.

Sandwich panels and shells will be provided by Boeing. These will comprise bonded and brazed panels with thin ALPORAS cores, configured as flat plates and curved shells. Tests performed on these sub-elements will be monitored by using full field strain mapping and, in some cases, X-ray CAT scanning. Three types of measurements will be performed:

(i) Edgewise compression tests will be used to examine face-sheet yielding and wrinkling, with emphasis on the role of "interface defects". The incidence of debonding will be examined and the post-yield deformation of the core characterized.

(ii) Cylinder indentation measurements will be used to establish local deformation modes and face-sheet/core interactions. Measurements of the strains will be made and simulations performed using the cellular material constitutive law. Debonding at the interfaces will be examined.

(iii) Flexural tests performed in three and four point loading will be analyzed in accordance with each of the associated deformation responses: bending, shear and indentation. Simulations will be used to deconvolute these deformations and to understand sub-element responses to concentrated loads. Face yielding, wrinkling and interface debonding will be monitored.

(iv) Energy Absorption

The energy absorption of tubular structures will be characterized. Calculations of the compressive shortening of shells and tubes with foam core walls, conducted in the presence of typical imperfections, will be used to establish domains in which the foam enhances the energy absorption. The effect of the foam properties on the achievable elevation will be established and used to guide the processing approaches required or energy absorbing structures.

The dynamic properties of the cellular metals will be characterized, especially their strain-rate dependence, using Hopkinson bar tests. These results will be used to address the influence of loading rate on the absorption characteristics.

(v) Minimum Weight Structures

Minimum weight designs will be analyzed for "generic" shell structures subject to multiaxial loadings. Comparisons between foam core and stiffened components will be made, where possible, in order to specify loading domains where weight savings can be achieved and to estimate their magnitudes.

(vi) Novel Architectures

Several stiff, strong cellular metal concepts have been identified. These include consolidated hollow spheres, hollow border materials and truss structures (JAM Corp.). The properties of each will be related to models, as well as compared with those for foam cast materials.

II. Thermal and Acoustic Performance

(i) Thermal Performance

Combined theoretical and experimental assessment of the heat transfer capabilities of open cell materials will calibrate the geometric coefficient that scales the heat transfer coefficient. The LSA model will be used to predict foam characteristics needed to achieve performance goals for high power electronic systems and heat exchangers. The effects of on the heat transfer of turbulence generated at the inlet will be measured by infrared imaging and used to find fluid flow conditions that maximize the overall heat transfer capability. Simultaneous measurements of the pressure drop will be taken and a correlation between the overall heat transfer and the pressure will be sought, analogous to similar correlations available for other porous materials.

The thermal properties of consolidated sphere materials will be measured and modeled, with the objective of relating the heat transfer coefficient to the morphology, density, thermal conductivity and fluid flow dynamics.

(ii) Acoustic Performance

An acoustic testing capability for cellular metals will be established and used to characterize the absorption as a function of sound frequency. Modifications to the cell walls will be made (such as rupture defects) and associated changes in absorption determined. The results will be correlated through models of the viscous dissipation and the heat conduction that occur as a result of dynamic interactions between the fluid and the cell walls. Both ruptured closed cells materials and open cell foams will be investigated.

III. Processing and Manufacturing

(i) Hollow Sphere Systems

Emphasis on hollow sphere systems, such as Ti-6-4 made by atomization and steel made by sintering, is motivated by their potential to exhibit greater stiffness and strength than foam cast materials. Such property enhancement is needed to realize performance advantages over competing systems in optimally-designed panels, tubes and shells. The spheres will be densely packed and consolidated by isostatic pressing as well as liquid phase sintering. Steel materials will be provided through collaboration with Cochran and

Sanders. Mechanical and thermal property measurements performed on these materials will be correlated with the packing, the contact diameter and the defects.

The potential for producing atomized hollow powders with relatively high internal pressures will be explored, as needed to create materials with low relative densities by means of a post-consolidation gas expansion treatment.

(ii) Low Density Core Materials

The importance of connected porosity on the occurrence of blisters will be systematically examined. Two approaches will be used. (i) The face sheets will be removed after HIPing and rolling to release the Ar pressure inside the porosity connected to the interface. New face sheets will be diffusion bonded onto the core and further rolling conducted. The occurrence of blistering will be compared with that found in conventionally made panels. (ii) The effect of powder size distribution on packing and the consequent connectivity of the porosity (permeability) after HIPing and rolling will be characterized.

It has been surmised that the relatively large non-proportional shear strains that arise near the core/face interface upon rolling may facilitate the formation of interfacial defects that subsequently initiate blisters. Numerical simulations of the rolling process will be performed with the objective of relating these shear strains to the rolling variables.

The refinement of the porosity that occurs in the rolling process may have consequences for blister formation and should be fundamentally understood. Attempts will be made to monitor the break-up of pressurized pores upon rolling.

Sensors that probe the evolution of the porosity in the pore expansion phase will be implemented and used to controllably achieve density goals.

(iii) Foam Casting

The effect of a Ni coating on the retardation of hydrogen release from TiH_2 particles in molten Al alloys will be measured. The retardation time will be used as a parameter to control bubble evolution and limit collapse effects that degrade the mechanical performance of the foam cast materials. This study will be conducted in collaboration with Banhart. Correlations will be made through models of gravitational drainage and pore coalescence.

(iv) Truss Structures

Rapid prototyping approaches will be explored as a means for producing truss structures and controlling properties, through collaboration with the MIT printing facility.

IV. Codes and Software

(i) FEM Code Development

Devising a constitutive law for cellular metals compatible with available finite element codes is essential for design as well as analysis of sub-element tests performed on panels and shells. A modified Drucker-Prager model has been calibrated by available experimental results and used to simulate the energy absorption. New results from shear tests, as well as multiaxial measurements, will be used to establish a generally applicable constitutive law.

Comparisons with the deformations measured in flexural tests and on compressed shells will validate the law before making it available for design purposes.

(ii) Software

New design features relevant to ultralight components will be incorporated into the CMS software. Results for the optimum design of panels and tubes with cellular cores will be introduced into the existing Shape sub-routine that compares structural indices for sub-elements subject to user defined combinations of axial, flexural and torsional loads. This feature will allow nomographs to be displayed that compare the performance of ULS systems with competing materials and designs.

D. List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

Interface cracking phenomena in constrained metal layers, M. Y. He, A. G. Evans, and J. W. Hutchinson, *Acta Mater.*, **44**, 2963-2971 (1996).

Models of high temperature, environmentally assisted embrittlement in ceramic-matrix composites, A. G. Evans, F. W. Zok, R. M. McMeeking and Z. Z. Du, *J. Amer. Ceram. Soc.*, **79,** 2345-52 (1996).

Design and life prediction issues for high-temperature engineering ceramics and their composites. Overview No. 125. A. G. Evans, *Acta mater.*, **45**, 23-40 (1997).

Mechanical performances of ceramic matrix composite I-beams. F. E. Heredia, M. Y. He and A. G. Evans, *Composites Part A*, **27A** (1996) 1157-1167.

Effects of off axis loading on the tensile behavior of a ceramic-matrix composite. C. S. Lynch and A. G. Evans, *J. Am. Ceram. Soc.*, **79**, (1996) 3113-3123.

A simple method for measuring surface strains around cracks, D. J. Wissuchek, T. J. Mackin, M. Degraef, G. E. Lucas and A. G. Evans, *Experimental Mechanics*,**36**, (1996) 173-179.

Strength-limited design of composite monolith transitions in metallic structures, F. W. Zok, M. Y. He, A. G. Evans, F. A. Leckie and H. E. Deve, *Composites Part A*, **28A** (1997) 399-407.

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Effect of interface undulations on the thermal fatigue of thin films and scales on metal substrates, A. G. Evans, M. Y. He and J. W. Hutchinson, *Acta Mater.*, **45** (1997) 3543-3554.

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Modeling of materials problems, M. F. Ashby, Special Volume of *Journal of Computer-Aided Materials Design*, **3**, 95-99 (1996)

The selection of actuators, J. Huber, N. A. Fleck, and M. F. Ashby, Proc. Royal Soc., London A (1997).

The micro-hardness of annealed and work-hardened copper polycrystals, W. J. Poole, M. F. Ashby and N. A. Fleck, *Scripta Materialia*, **34,** 559-564 (1996).

The optimal selection of materials and section-shape, P M. Weaver and M. F. Ashby, *J. Eng. Design,* **7,** 129-150 (1996).

Choix et usage des materiaux, M. F. Ashby, Y. Brechet, M. Dupeux and F. Louchet, *Techniques de l'engenieur,* Editions Maurice Postel, S. A. Paris, France, Volume **T-5-100,** 1-23 (1996).

Selection of materials to reduce environmental impact: a case study on refrigerator insulation, M. F. Ashby, S. C. Burgess, N. Shibaike and P M. Weaver, *Materials and Design*, **17**, 11-17 (1996).

The machining of sintered bronze, N. A. Fleck, K. J.Kang and J. A. Williams, *Int. J. Mech. Sci.*, **38**, pp.141-155 (1996).

Micro-hardness tests on annealed and work-hardened copper polycrystals, W. J. Poole, M. F.Ashby and N. A. Fleck, *Scripta Met. et Mat.* **34**, pp.559-564 (1996).

Prediction of compressive toughness for fibre composites, M.P.F.Sutcliffe, N.A. Fleck, and X.J. Xin, *Proc. Roy. Soc. Lond. Series A,* **452**, pp. 2443-2465 (1996).

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Compressive R-curve of a carbon fibre - epoxy matrix composite, N. A. Fleck, M. P. F., Sutcliffe, S. Sivashanker and X. J. Xin , *Composites Part B*, **27B**, pp. 531-541(1996).

Microbuckle propagation in a unidirectional carbon fibre - epoxy matrix composite, S. Sivashanker , N. A. Fleck and M. P. F. Sutcliffe, *Acta Materiala,* **44**, pp. 2581-2590 (1996).

Dynamic compressive failure of fiber composites, W. S. Slaughter, J. Fan and N.A. Fleck, *J. Mech. Phys. Solids*, **44**, 1867-1890 (1996).

The role of strain gradients in thegrain size effect for polycrystals, V. P. Smyshlyaev and N. A. Fleck, *J. Mech. Phys. Solids*, **44**, 465-495 (1996).

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Microbuckle propagation in fibre composites, M.P.F. Sutcliffe and N.A. Fleck, *Acta Mater.*,**45**, 921-932 (1997).

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Nonlinear delamination mechanics for thin films, Y. Wei and J. W. Hutchinson, *J. Mech. Phys. Solids.,* **45** 1137-1159 (1997).

Composite laminates in plane stress: constitutive modeling and stress redistribution due to matrix cracking, G. M. Genin and J. W. Hutchinson, *J. Amer. Ceram. Soc.,* **80,** 1245-55 (1997).

Convergent debonding of films and fibers, M. Y. He, A. G. Evans and J. W. Hutchinson, *Acta. mater.*, **45,** 3481-89 (1997);

Steady-state crack growth and work of fracture for solids characterized by strain gradient plasticity, Y. Wei and J. W. Hutchinson, *J. Mech. Phys. Solids*, **45** 1253-1273 (1997).

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Eddy Current Sensing of Vertical Bridgman Growth, K. P. Dharmasena and H.N.G. Wadley, J. *Crystal Growth*, **172**, 337-349, (1997).

Eddy Current Determination of the Electrical Conductivity-Temperature Relation of Cd1-x ZnxTe Alloys H.N.G. Wadley and B.W. Choi, *J. Crystal Growth*, **172**, 323-336, (1997).

2. Non-Refereed Publications and Published Technical Reports.

Porous Metals and Metallic Foams, A. E. Simone, Ph.D. Thesis, Department of Civil and Environmental Engineering, MIT, July 1997.

Computer Based Selection of Manufacturing Processes, A. M. K. Esawi and M. F. Ashby, Cambridge University Engineering Dept., Report EDC/TR-50, May 1997.

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Compressive failure of composites due to microbuckle growth,N. A. Fleck , S.Sivashanker, and M. P. F. Sutcliffe , *Eur. J. Mech., Solids,* **16**, 65-82 (1997).

The viscoplastic compaction of powders, N.A. Fleck, B. Storakers and R.M. McMeeking, IUTAM Symposium on Mechanics of Granular Flow and Powder Compaction, 15-17 July 1996, Cambridge, England, N. A. Fleck and A. C. F. Cocks, eds., Kluwer Academic Publishers, Amsterdam (1997).

Edge-cracks in single crystals under monotonic and cyclic loads, J. W. Hutchinson and V. Tvergaard, Harvard University, Mech 307, Cambridge, MA (1997).

The mechanics of size-dependent indentation, M. B. Begley and J. W. Hutchinson, Harvard University, Mech 309, Cambridge, MA (1997).

Spherical impression of thin elastic films on elastic-plastic substrates, M. B. Begley, A. G. Evans, and J. W. Hutchinson, Harvard University, Mech 314, Cambridge, MA (1997).

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Fleck, N. A. and Cocks, A. C. F., eds., Proceedings of the IUTAM Symposium on Mechanics of Granular and Porous Materials, 1997, Kluwer Academic Publishers.

3. Presentations

a. Invited

A. G. Evans, MIT, Mechanical Engineering, Septepmber 1996

A. G. Evans, Engineering Foundation, Davos, Switzerland, May 1996

A. G. Evans, Max Planck Institute, Stuttgart, Germany, May 1996

A. G. Evans, International Sceince Lecture Series, China and Hong Kong, September 1996

A. G. Evans, Defense Science Research Council, July 1996

A. G. Evans, IBM, East Fishkill,NY, January 1996

L. J. Gibson and A. E. Simone, Aluminum Foams: Structure and Properties, Invited Mechanics and Materials Seminar at the Department of Mechanical Engineering, MIT, April 2, 1997.

L. J. Gibson and A. E. Simone, Aluminum Foams: Structure and Properties, Invited Seminar at MURI Workshop of Ultralight Metal Structure, April 18, 1997.

L. J. Gibson, Aluminum Foams: Structure and Properties, Invited Seminar at the Department of Materials, Georgia Institute of Technology, April 22, 1997.

M. F. Ashby, Materials Selection, A short course at UCLA, March 1997.

M. F. Ashby, Materials Selection, A short course at the University of Trondheim, Norway, May, 1997.

M. F. Ashby,The Structure and Properties of Metal Foams: A Database, Bremen Conference on Metal Foams, Bremen, Germany, March 1997.

B. Budiansky, On Kink-Band Propagation in Fiber Composites. Presented at ASME Winter Annual Meeting, Atlanta, November 1996.

N A. Fleck, Plenary lecture on 'Compressive Failure of Engineering Materials', Euromech, 3 Congress, Stockholm, 20-24 August 1997.

J. W. Hutchinson, Thin Films and Multilayers, Technical University of Denmark, Lynby, Denmark.

J. W. Hutchinson, Thin Films and Multilayars, National University of Singapore, Singapore.

J. W. Hutchinson, Scales and Fracture, Keynote Lecture, Int. Fracture Conference, Sydney, Australia.

J. W. Hutchinson, Thin Films and Multilayers, Alborg University, Alborg, Denmark.

J. W. Hutchinson, Strain Gradient Plasticity, Technical University of Delft, Delft, The Netherlands.

J. W. Hutchinson, Strain Gradient Plasticity, Ecole Polytechnique, Paris, France. (1997)

H. N. G. Wadley, Model-based Optimization of Consolidation Processes TMS Annual Meeting Orlando, FL, February 10-13, 1997

H. N. G. Wadley, Atomistic Modelling the Physical Vapor Deposition of Metals: Needs andOpportunities Monitoring and Control Techniques for Intelligent Epitaxy II, Kananaskis Village, Alberta, Canada, April 7-8, 1997

H. N. G. Wadley, Intelligent Processing of Thermal Barrier Coatings Intelligent TMCConsolidation Works Workshop ,University of Virginia, May 6, 1997.

H. N. G. Wadley, Directed Vapor Deposition, Multiscalar Modelling and Intelligent Control, DARPA-FAME Workshop Arlington, VA, May 15, 1997

H. N. G. Wadley, Atomistic Modelling for Simulating the Physical Vapor Deposition of GMR Multilayers DARPA Magnetic Materials and Devices Spintronics Workshop Mesa, AZ, May 29-30, 1997

H. N. G. Wadley, Atomistic Modelling of Metal Multilayer Synthesis DARPA/NSF Virtual, Integrated Prototyping Workshop Stanford University, Palo Alto CA,July 1- 2, 1997

H. N. G. Wadley, Intelligent Processing of Materials Case Western Reserve University Colloquium Series Cleveland, OH .March 4, 1997

H. N. G. Wadley, Novel Concepts for Unmanned Vehicles DARPA/DSRC Uninhabited Vehicle Study Meeting Rosslyn, VA April 16, 1997

H. N. G. Wadley, Atomistic Modelling Physical Vapor Deposition UVA School of Engineering & Applied Science Chemical Department Seminar, September 12, 1997

b. Contributed

A. E. Simone, Mechanical Behavior of Foamed Aluminum, ASME Symposium on Cellular and Microcellular Materials at the Winter Annual Meeting of the ASME, Atlanta, November 17-22, 1996.

4. Books

Gibson, L. J. and M. F. Ashby (1997) Cellular Solids: Structure and Properties, Second Edition, Cambridge University Press, Cambridge, UK.

Ashby, M. F. The Chapman and Hall Materials Selector, (A 3-volume reference work with N. A. Waterman), Chapman and Hall, London, January 1997.

Ashby, M. F., Cellular Solids, (with L. J. Gibson) Cambridge University Press, January 1997.

E. LIST OF HONORS/AWARDS

Awards

Name of person receiving award	Recipient's Institution	Name, Sponsor and Purpose of Award
Lorna J. Gibson	MIT	Matoula S. Salapata Professorship of Materials Science and Engineering, MIT
M. F. Ashby	Cambridge University	Commander of the British Empire. An honor awarded by the British Government and presented by the Queen, for public services, in this case for Service and Materials Science, Engineering and Design.
N. A. Fleck	Cambridge University	Chair of Mechanics of Materials Fellow of the Institute of Materials Chartered Engineer.
H. N. Wadley	University of Virginia	Edgar A. Starke, Jr. Research Professorship in Materials Science Fellow,American Society of Materials, International
A G. Evans	Harvard University	National Academy of Engineering

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A G. Evans	Harvard University	National Academy of Engineering

H. SUMMARY OF FY96
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS/PARTICIPANTS
(Number Only)

		ONR	non ONR
a.	Number of Papers Submitted to Referred Journal but not yet published:	20	15
b.	Number of Papers Published in Refereed Journals:	45	32
c.	Number of Books or Chapters Submitted but not yet Published:	0	0
d.	Number of Books or Chapters Published:	3	2
e.	Number of Printed Technical Reports & Non-Referred Papers:	0	0
f.	Number of Patents Filed:	0	0
g.	Number of Patents Granted:	0	0
h.	Number of Invited Presentations at Workshops or Prof. Society Meetings:	30	17
i.	Number of Contributed Presentations at Workshops or Prof. Society Meetings:	0	0
j.	Honors/Awards/Prizes for Contract/Grant Employees: (selected list attached)	5	
k.	Number of Graduate Students and Post-Docs Supported at least 25% this year on contract grant:		
	Grad Students: TOTAL	20	12
	Female	6	3
	Minority	1	1
	Post Doc: TOTAL	6	3
	Female	1	1
	Minority	0	0
l.	Number of Female or Minority PIs or CO-PIs		
	New Female		
	Continuing Female	1	0
	New Minority		
	Continuing Minority		

Enclosure (4)